Reactions of Cesium with Protons at 60, 80, 100, 150, and 240 Mev*

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Absolute production cross sections have been determined for certain isotopes of barium, cesium, iodine, and tellurium produced by reactions of cesium with protons of energies 60, 80, 100, 150, and 240 Mev. The yields are based on the known cross section for the monitor reaction $Al^{27}(p,3pn)Na^{24}$. In the region up to 100 Mev the data indicate that the yields are largely explained on the basis of an evaporation mechanism which competes with the prompt knock-on optical model to an extent which decreases rapidly with increasing energy because of increasing nuclear transparency. The neutron pick-up reaction manifests itself in extraordinarily large yields of Cs^{132} and to a lesser extent in the yields of Cs^{131}. Formation of small amounts of neutron-excess iodine isotopes argues for alpha-particle fragmentation especially at the lower bombardment energies.

INTRODUCTION

PREVIOUSLY[1] we have reported on the spallation of cesium with 240-Mev protons from the Rochester 130-inch cyclotron. The results indicated that a majority of reactions at 240 Mev occur as primary knock-on collisions in which the incident proton interacts with only a few nucleons. This primary interaction is followed by dissipation of the residual nuclear excitation, whose energy spread is quite broad, leading to a distribution of products which reach far down the nuclide chart. At an energy of 240 Mev those yields due to the knock-on process largely predominate over those due to an evaporation mechanism because of the nuclear transparency[2] which increases with energy rapidly up to roughly 200 Mev and then much more slowly up to about 400 Mev.

In this paper we report the behavior at a variety of proton energies; namely, 60, 80, 100, 150, and 240 Mev. The experimental techniques are identical with those reported earlier,[1] as are all of the assumptions and correction factors which are applied to obtain the yield of each nuclear species.

The results are given in Table I, which also lists the counting efficiency used for each nuclide. This efficiency is defined as the ratio of the number of events recorded in the beta-proportional methane flow counting chamber to the total number of events occurring within the sensitive volume of the chamber. The values are identical to those given previously with the exception of Cs^{132}. We have reconsidered the value of the counting efficiency for this nuclide and have used a value of 0.01 in place of the value of 0.005 used formerly. The yield of Cs^{132} at 240 Mev given in our first paper should therefore be revised to that given in Table I.

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[1] R. W. Fink and E. O. Wiig, Phys. Rev. **94**, 1357 (1954).
[2] J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950); J. DeJuren, Phys. Rev. **80**, 27 (1950).

BARIUM YIELDS

Figure 1 depicts the yield data for barium isotopes taken from Table I. It is seen that the yield of Ba^{128} has a threshold of about 60 Mev and a maximum at approximately 80 Mev. The relative shape of these yield curves must be attributed to differences in average excitation energies imparted to the struck target nuclei by the incident protons. In general, lower bombardment energies result in lower average excitation energies left to the struck nuclei. Consequently, the broad peaks must result from a rather wide distribution of smaller excitation energies given to the excited nuclei following an initial knock-on reaction. Subsequent evaporation ejects protons and neutrons either singly or in fragments such as alpha particles. The maximum yield of each barium isotope in Fig. 1 occurs in the expected sequence Ba^{131}, Ba^{129}, and Ba^{128}. Apparently the hump

TABLE I. Absolute production cross sections of spallation products resulting from irradiation of cesium with protons at various energies.[a]

Nominal half-life	Nuclide	Counting efficiency	60 Mev	80 Mev	100 Mev	150 Mev	240 Mev
				(Yields in millibarns)			
2.4 days	Ba^{128}	1.0	0	67	58	14	8.1
2.0 hr	Ba^{129}	1.0	173	3.1	4.7	11	3.6
12.5 days	Ba^{131}	0.72	20	4.8	13	3	5.3
42.5 hr	Ba^{133m}	0.78	31	—	—	—	—
5.5 hr	Cs^{127}	1.0	0	7.1	15.4	6.4	4.5
31 hr	Cs^{129}	0.4	83	123	116	36	15
30 min	Cs^{130}	1.0	137	46	—	12	—
9.8 days	Cs^{131}	0.0025	470	—	500	320	460
7.1 days	Cs^{132}	0.01	790	1120	890	570	59
1.6 hr	$I^{120+121}$	1.0	0	0	0	3.6	11
13 hr	I^{123}	0.17	0	0	0	8.5	21
4.0 days	I^{124}	0.30	0	0	0.9	5.7	8.4
12.5 days	I^{126}	0.53	0.05	0.94	2.4	2.5	5.0
25.0 min	I^{128}	0.95	0.36	0.4	0.44	—	—
12.6 days	I^{130}	1.0	0.004	0.02	0.04	—	—
2.5 hr	Te^{117}	1.0	0	0	—	0.2	2.4
6.0 days	Te^{118}	1.0	0	0	—	1.1	4.8
17.0 days	Te^{121}	0.1	—	—	7.3	5.1	—

[a] Energies quoted are nominal beam energies of the Rochester 130-inch cyclotron as estimated from radius. Places in the table showing a yield of 0 millibarns signify that in those instances the nuclide should have been observed had it been present, so that a 0 yield signifies a lack of production of detectable amounts of the nuclide. Places showing a dash (—) signify that in those instances the nuclide might have been present in small amounts but could not be detected and identified because of experimental difficulties such as (a) the time for chemical separation was too long; (b) other species of similar half-life or stronger radiations were produced at that energy, causing masking; or (c) the yield was too small to be detected or identified.

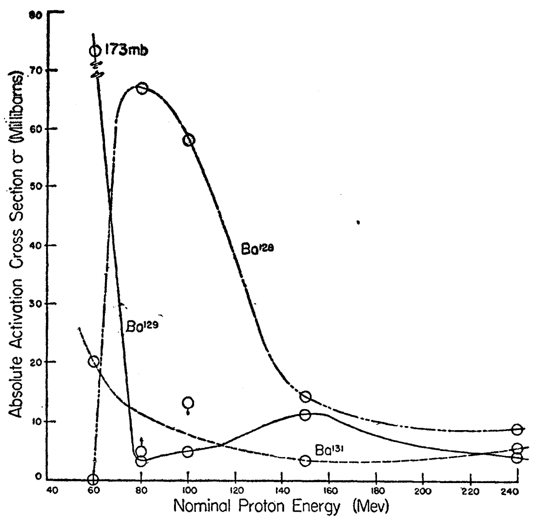

FIG. 1. Variation of the yields of barium isotopes with proton bombardment energy.

in the yield curve of Ba^{129} in the 150-Mev region is real. Caretto[3] has observed a similar maximum in the region of 175 Mev for the yields of several nuclides produced by the reaction of protons on yttrium. If this maximum is real, it might be explained on the basis that at energies between 80 and 100 Mev, the production cross sections of Ba^{128}, Cs^{129}, Cs^{131}, and Cs^{132} compete severely with that of Ba^{129}, lowering the yield of the latter in this region. As the excitation energy is increased, this competition becomes less pronounced and a rise occurs in the Ba^{129} yield curve above 100 Mev.

CESIUM YIELDS

Figure 2 presents the yield data for cesium isotopes from Table I. The yield of Cs^{132} is seen to be extraordinarily high, especially in the neighborhood of 80 to 100 Mev, compared to the yields of its immediate neighbors, Cs^{131} and Cs^{130}. This observation can probably be explained on the basis of the neutron pick-up reaction, $Cs^{133}(p,d)Cs^{132}$. Several investigators at Berkeley[4] have observed that irradiations of elements with 90-Mev neutrons result in unexpectedly large yields of deuterons of energy of the same order as the incident neutrons and sharply peaked in the forward direction. The high yield, high emission energy, and the angular distribution peaked sharply forward all suggest that a production mechanism is responsible which involves the "pick-up" of a neutron by an incident proton, or vice versa, according to the suggestions of Chew and Goldberger.[5] To a much smaller extent the pick-up process also operates to form tritons, in which the incident proton and two neutrons in the target nucleus happen to possess momenta relative to each other which is compatible with the internal motion of a triton. To a certain extent then, we expect a contribution to the yield of Cs^{131} from the pick-up reaction $Cs^{133}(p,t)Cs^{131}$, but the effect is much less pronounced than that due to the (p,d) reaction in Fig. 2. One would expect a gradual decrease in the contribution from pick-up reactions with increasing energy, which is borne out experimentally by the yield curve of Cs^{132} which falls off only gradually as compared with the yield curves of barium and other cesium nuclides which fall off rapidly. A reaction threshold for the formation of Cs^{127} of about 55 Mev is also indicated by the data in Fig. 2. The other general features of the cesium yield curves can be explained on the same basis of average excitation energies as the barium curves.

IODINE YIELDS

Figure 3 indicates the yield pattern of the $(Z-2)$ product, iodine, from the data in Table I. These curves, very different from the yield curves for barium and cesium in the region below 150 Mev, show that the formation of neutron-deficient iodine isotopes occurs only at higher energies. There are no salient peaks at lower energies, indicating little if any contribution from an evaporation mechanism below 100 Mev. This is in marked contrast to cesium and barium yields which show large contributions from the evaporation model below 100 Mev. It is clear that the neutron-deficient iodine isotopes are formed above about 100 Mev chiefly from the knock-on process, although some evaporation may redistribute the iodine yields following the initial knock-on reaction. In the case of the neutron-excess isotope I^{128} the yield which appears in Table I below 150 Mev probably can be attributed to alpha-particle emission, due to lower excitation energies in the struck nucleus, as well as to evaporation. The yield of I^{130} is still smaller by at least one order of magnitude and would require the emission of the equivalent of He^3 from

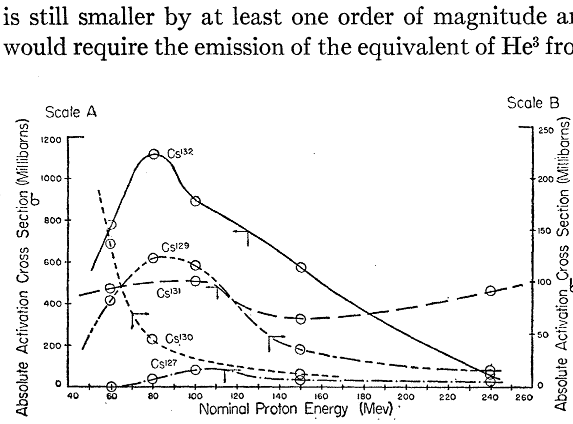

FIG. 2. Variation of the yields of cesium isotopes with proton bombardment energy. Note that two ordinates are used; the arrows indicate which scale applies to a particular curve.

[3] A. A. Caretto, Jr., Ph.D. thesis, University of Rochester, 1953 (unpublished).

[4] A. Bratenahl, University of California Radiation Laboratory Report UCRL-1842, 1952 (unpublished); J. Hadley and H. F. York, Phys. Rev. **80**, 345 (1950); K. Brueckner and W. M. Powell, Phys. Rev. **75**, 1274 (1949); H. Bradner, Phys. Rev. **75**, 1467 (1949).

[5] G. Chew and M. Goldberger, Phys. Rev. **77**, 470 (1950).

the excited target nucleus. Emission of alpha particles increases the neutron/proton ratio of the product which may account for the augmented yield of I^{128} at the lower energies. Formation at these energies of such shielded isotopes as I^{124}, I^{126}, and I^{128} is also an indication of alpha-particle fragmentation.

The apparent threshold for formation of $I^{120+121}$ and I^{123} is about 100 Mev; for formation of I^{124}, about 80 Mev; and for I^{126}, about 60 Mev. The reason that the yields of I^{123} are larger than those of its neighbors up to the highest energy studied, 240 Mev, must be associated with the assumption that in the range 140 to 240 Mev, the average excitation energy given to the struck target nucleus must be such as to favor the reaction leading to I^{123}. Thus, as the bombardment energy is increased to 240 Mev from the lowest value, each iodine isotope starting from stable I^{127} is in turn the product of a favored reaction, the yields first rising successively and then eventually flattening out. Thus, in Fig. 3, the yield of I^{126} rises first and flattens out soonest; next comes I^{124}, rising and then flattening out; then I^{123}, the most favored product between 140 and 240 Mev, which possibly would flatten out at still higher energies; finally, the yield of the most neutron-deficient isotope(s) $I^{120+121}$ is still rising at 240 Mev and presumably would reach and surpass that of I^{123} at much higher energies. Consequently, it is clear that the iodine yield curves can be explained qualitatively on the picture of successively higher average excitation energies imparted to the target nuclei with a particular reaction being favored over the others at a given average excitation energy.

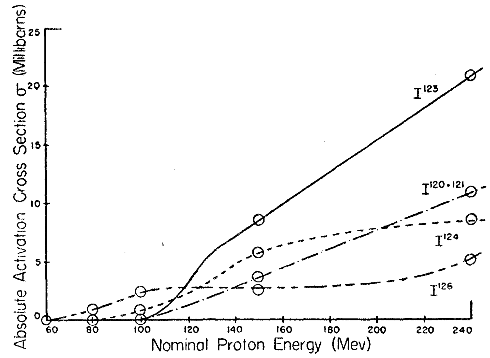

FIG. 3. Variation of the yields of iodine isotopes with proton bombardment energy.

TELLURIUM YIELDS

Yields of tellurium isotopes are given in Table I, but are not plotted. In common with the iodine results, the data for the more neutron-deficient isotopes Te^{117} and Te^{118} indicate a production threshold near 100 Mev and yields that increase with energy.

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